

APPENDIX MS4. VARIABLE IMPACTS OF FUTURE FISHERIES DEVELOPMENT IN THE CALIFORNIA CURRENT ON ECOSYSTEM STABILITY AND SPATIALLY EXPLICIT BIOMASS PATTERNS

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ABSTRACT

Studies have demonstrated the importance of large biomass forage groups in model food webs, but small biomass contributors are often overlooked. Here, we predict impacts of three potential fisheries targeting relatively low biomass functional groups in the California Current Atlantis Model: deep demersal fish, nearshore miscellaneous fish, and shortbelly rockfish (*Sebastes jordani*). Using a spatially explicit ecosystem model, we explored fishing scenarios for these groups that resulted in depletion levels of 75, 40, and 25 percent. We evaluated the effects of fishing on ecosystem-wide biomass and spatial distribution of biomass. We also investigated the effects of fishing on ecosystem stability using multivariate time-series methods. Results indicate that developing fisheries on the proposed targets would have low impacts on biomass of other species at the scale of the whole California Current ecosystem. Ecosystem stability declined with fishing pressure, however. The spatial distribution of impacted functional groups was patchy, and concentrated in the central California region of the model. This work provides a framework for evaluating impacts of new fisheries with varying spatial distributions and suggests that regional effects should be evaluated within a larger management context.

INTRODUCTION

Human demands on ocean production have never been higher [1]. High demands for fish and fishmeal have led to fishing activities targeting lower trophic level species than in previous decades [2-4]. Increasing demands on already taxed ecosystems can lead to difficult management decisions regarding trade-offs between consumptive and non-consumptive uses of these forage groups. Ecosystem based management is one approach that identifies trade-offs in an ecosystem context, allowing for cumulative impact assessment across sectors [5,6].

Fishery management in the U.S. has been moving towards ecosystem based management approaches for more than a decade. In 1999, a panel of experts convened by the National Marine Fisheries Service (NMFS) recommended that regional fishery management councils adopt Fishery Ecosystem Plans as a supplement to existing Fishery Management Plans [7]. The goal of a fishery ecosystem plan is to document the structure and function of the managed ecosystem, including two-way feedbacks between the ecosystem and fishing activities. Fisheries ecosystem plans have been developed for regions such as the North Sea, Aleutian Islands, Pacific Islands, and Chesapeake Bay [8-11]. The Pacific Fishery Management Council is currently developing a Fishery Ecosystem Plan [12], targeting the California Current Large Marine Ecosystem (CCLME). The plan is still in draft form, however current objectives include addressing gaps in ecosystem

knowledge with respect to effects of fishing on marine ecosystems and considering the potential of developing science and management at spatial scales relevant to stock structure [12].

The ecosystem effects of fishing high biomass, low trophic level species have been the targets of much research recently [13,14, Kaplan et al. this volume]. These groups, by definition, form the base of the pelagic food web, and are important prey species for many higher trophic level species that are of commercial importance and/or conservation concern. Fishing limits have been put into place to protect high biomass, low trophic level species such as krill, anchovy, and sardine [15,16].

Studies on the impacts of fishing forage groups often focus on species or groups that contribute large amounts of biomass to large marine ecosystem [2], while low biomass groups are more easily overlooked. Fishing on these groups may indeed have few impacts on food webs if species are functionally redundant to large biomass prey species [17]. Or, removals of low biomass groups may have disproportionate impacts, depending on their role in the ecosystem and spatial distribution and overlap of predators and prey. For example, central place foragers, like many seabirds, depend on locally abundant seasonal prey resources [14,18,19]. Fluctuations in these resources could have severe impacts on populations that rely on them, even if overall biomass is low [20].

In this study, we investigated the effects of targeted fisheries on relatively low biomass forage fish species in a large marine ecosystem. Similar to previous modeling studies we report biomass responses of species in the food web. However this work is novel in that we also describe the effects of fishing on ecosystem stability, and explore biomass impacts using a spatially explicit model to predict the regional distribution of these impacts. We explored whether fishing these species under various fishing mortality scenarios affected other species in proportion to their overall biomass in the ecosystem. We investigated target species that were broadly and narrowly distributed within the region to explore the effects of spatial variation on fishery development.

METHODS

MODEL FRAMEWORK

Atlantis is a three dimensional, spatially explicit ecosystem model, comprised of three sub-models [21]. The oceanographic sub-model simulates physical transport using output from a Regional Ocean Modeling System to track temperature, salinity, and circulation. The ecological sub-model captures nitrogen and silicon dynamics through trophic interactions among cells, representing functional groups from bacteria and plankton to fish and marine mammals. The human impacts sub-model overlays both the ecological and oceanographic sub-models, and includes fisheries, nutrient inputs, and management control rules. This framework allows for hypothesis testing of how perturbations in the food web can propagate all the way to the management arena. Fulton and colleagues [22] summarize the assumptions and options within the Atlantis code base, and detail lessons learned from 13 recent modeling efforts.

The Central California Atlantis Model (CCAM) was developed to address federal and state level management needs in the California Current Large Marine Ecosystem [23,24]. The modeled area extends from Cape Flattery in the north to Point Conception in the south and from shoreline to the 2400 m isobaths (Figure 1). There are 12 latitudinal regions, broken up longitudinally by 3 to 7 depth zones. Each of these two dimensional areas is further divided into up to seven depth bins, capturing the sediment layer to the surface layer through the water column. The central California region of the model has higher 2-d spatial resolution

in depth zones than the northern and southern regions. CCAM oceanography is based on a ROMS time-series for 1958-2004.

The ecological sub-model for CCAM compartmentalizes biomass among 62 functional groups. Species are grouped based on similar life history characteristics and diets. Details of model parameterization and calibration have been described elsewhere [23,24].

We used a “status quo” fishing scenario against which to compare all new fishing activities in the model. The status quo represented current fishing in the CCLME, and was the same as in Kaplan et al. [24]. Spatial closures represented current area-based management, and fishing mortalities were specified by targeted group and fleet and calibrated to reproduce catches from stock assessments, where applicable [23].

APPROACH

For each new target group, we created a new fleet in the model and determined the appropriate area closures based on the likely gear type. We ran fishing scenarios for each fishery addition following methods by Smith et al. [13] and Kaplan et al. (this volume). We incrementally increased the annual fishing mortality from zero until the target group was completely depleted. Each model run was 50 years, allowing functional groups to reach quasi- equilibrium; the model does not assume true equilibrium dynamics and is driven by oceanographic forcing as well as species interactions. We then used these fishing mortalities and resulting catches to determine the maximum sustained yield (MSY) for each group, as well as the fishing mortality required to obtain 3 levels of depletion relative to the status quo fishing scenario: 25 percent, 40 percent, and 75 percent of status quo biomass.

We describe the impacts of the new fisheries on equilibrium yields and biomasses of the other functional groups in the model. We averaged the last five years of each model run to represent an equilibrium catch or biomass for the majority of functional groups. However, groups with high growth rates and quick turnover tend to have flashy dynamics. For these groups (all plankton, zooplankton, and bacteria) we averaged over the last 20 years of each model run.

We used a threshold of ten percent change in catch or biomass to determine whether the new fishery impacted functional groups. The choice of threshold was somewhat arbitrary—Smith et al. used 40 percent, Kaplan et al. used 20 percent. Because our target species were lower biomass than the groups previous studies investigated, we set a lower threshold.

We also investigated the effects of fishing on ecosystem stability. Stability is a property that describes the response of an ecosystem to a perturbation [25], and may also relate to regime shifts [26]. To estimate stability, we fit multivariate auto-regressive (MAR) models to the last 10 years of Atlantis model output by cell, and estimated the ecosystem-wide community or interaction matrix for all functional groups following methods of Ives et al. [27]. We estimated three metrics of system stability derived from the community matrix (**B**)—two that relate to asymptotic stability and one that describes transient behavior after a perturbation. These well-established methods have been used to describe stability properties from time-series in both modeled and data-based food webs [28,29].

The dominant (largest) eigenvalue of the community matrix describes the rate of return of an ecosystem following a perturbation, and is the most commonly used metric of stability describing resilience (return rate). An alternative to this metric takes into account all of the eigenvalues of the community matrix: $\det(\mathbf{B})^{2/p}$ where p is the number of groups in the model [27]. We refer to this second metric as stability.

Reactivity describes transient activity immediately after a perturbation, rather than long-term patterns of return [30]. We calculated a worst-case reactivity from the community matrix: $\max(\lambda_{B'B})$ [27].

DEEP DEMERSAL FISH

The deep demersal fish group in CCAM is distributed along the continental slope (500-1200 m, Figure 1 A), and consists mostly of giant grenadier (*Albatrossia pectoralis*) and Pacific grenadier (*Coryphaenoides acrolepis*). Other species in this functional group include Pacific lamprey, eelpouts, cusk eels, and poachers [23]. The west coast groundfish fleet catches both grenadier species, and Bellman et al. [31] estimated one to two percent of the annual catch at depths greater than 250m consists of giant and Pacific grenadier, totaling 600 mt per year. These species are rarely landed because of limited market demand [32]. A pot fishery for lamprey is also included in CCAM with harvest of 1250 mt per (Table 1).

Grenadier (family Macrouridae) catches around the world have risen since the mid 1990s. Targeted fisheries currently harvest about 45000 mt of grenadier from the world's oceans each year [33]. In the North Pacific, Japanese harvested grenadier during the 1980s. They were processed into surimi, before the walleye Pollock fishery became a more marketable source [32]. Due to historical use and increasing demand for fish and fish products, we thought it would be useful to explore the potential impacts of landing this species complex on the west coast.

Natural mortality for the deep demersal fish group is low (0.1, Table 1), which suggests a priori that MSY will also be relatively low. We created a target fishery on this group that represents a fishery for grenadier using the same gear and area restrictions as the existing bottom trawl fleet [24].

NEARSHORE MISCELLANEOUS FISH

The nearshore miscellaneous fish group is a catchall group dominated by white croaker (*Genyonemus lineatus*), but also includes shallow sculpins and midshipman. This group is distributed across the nearshore model domain, with higher densities in central California than other regions (Figure 1B). Life history parameters for this group are based on white croaker [23].

We created a fishery on this group primarily to represent a fishery targeting white croaker. Croaker is a popular recreational target in California, but only small amounts are currently landed in commercial fisheries annually (3 mt in 2011) using round haul net, gill net, and hook and line gear [34]. Atlantic croaker (*Micropogonias undulatus*) is a closely related species on the east coast of the US, with similar size, life history, and habitat and food preferences [35,36]. Atlantic croaker is the target of a valuable 10000 mt fishery [33].

While the distribution of the miscellaneous nearshore fish group spans the latitudinal extent of the model domain, in reality, white croaker likely composes greater proportions of the group's biomass from San Francisco bay south to Point Conception [37]. An existing modeled recreational fishery accounts for 247 mt of biomass removed from this group each year. The natural mortality rate for the group is 0.62, suggesting it would tolerate a moderate harvest rate (Table 1). We created a target fishery for croaker using the same area closures as the existing nearshore non-fixed gear sector [24].

SHORTEBELLY ROCKFISH

Shortbelly rockfish is the most abundant of the rockfish species, and in CCAM shortbelly comprise their own functional group. The most current stock assessment estimated the shortbelly stock to be 64,000 mt in 2005 [38]. Notably, modeled shortbelly biomass in our status quo scenario is roughly 25 percent of the assessed biomass (Table 1). Considerable biomass uncertainty likely results from a lack of fishery dependent data and poor catchability of shortbelly in the fisheries independent trawl survey [38]. Shortbelly rockfish density is highest in central California (Figure 1C). A few fleets unintentionally catch shortbelly, but these removals are limited to less than 1 mt per year [31]. A relatively high natural mortality rate in CCAM (0.35) suggests that this group should be able to sustain a moderate level of fishing mortality (Table 1). We modeled the shortbelly fishery as a mid-water trawl fishery, subjected to the same area closures as the existing trawl fleet [24].

Fishery interest in shortbelly rockfish has historically been quite low, at least in part because shortbelly is small-bodied (maximum size less than 30 cm) [38,39]. Lenarz [39] identified a potential pet food or surimi market for shortbelly, however he also pointed out these were not economically viable as of 1980. Currently, an annual catch target of 50 mt is in place for shortbelly. The groundfish catch regulations indicate this limit is higher than recent catches of shortbelly, but the target is set conservatively because shortbelly is an important forage species in the California Current ecosystem [40,41].

RESULTS

We found some general and some variable effects of fishing the new target groups. First, we describe overall general patterns of ecosystem response. Then, we describe specific results of fishing each target group on biomass, yields and stability.

Across all fishing scenarios and target groups, we saw limited ecosystem-wide effects of fishing on biomass or yields of other groups. The impacts we did observe were disproportionately weighted in the central California region of the model. No predators of the three target groups were affected by their removal. Nine invertebrate groups (planktonic and benthic) were affected in one or more model cells by at least one of the fishing scenarios. In some cases, affected groups were prey of target species, but in others they were more than one trophic link removed from the fished group. Likewise, not all impacted model cells contained the target species. Notably, the vast majority of impacted groups were highly productive and demonstrated oscillatory or eruptive behavior.

We attempted to explain variation in the number of groups impacted in each model cell using cell area, cell volume, total number of functional groups present, density of target group, density of prey groups (of target), and density of affected groups. However, preliminary analyses showed no relationships between any of these variables.

Fishing the deep demersal, nearshore miscellaneous, and shortbelly groups had variable effects on ecosystem stability (Table 2). The stability metric that took into account only the dominant eigenvalue of the community matrix, return rate, was least sensitive to the effects of fishing. Alternatively, the metric that weights all of the eigenvalues (what we refer to as stability) generally showed destabilizing effects of new fishing activity. Reactivity generally decreased initially with fishing effort, but increased as the target group became depleted.

DEEP DEMERSAL FISH

Simulations suggested that deep demersal fish could sustain a maximum harvest of 2055 mt per year, which required annual fishing mortality of 0.03. This level of fishing reduced the biomass of this group to 66747 mt (about 40 percent of the status quo biomass, appendix 1). The current estimate for grenadier bycatch is 600 mt [31], resulting in capacity for a fishery using the same gear as the current trawl fishery of about 2600 mt sustained yield.

Fishing deep demersals had no impact on fishery yields or abundance of any other functional group at the scale of the whole ecosystem (using a 10 percent threshold), despite the group's broad latitudinal distribution. Individual cells were affected primarily in the Central California region. There, a new fishery affected biomass of up to three invertebrate functional groups in the plankton and benthos, some of which were prey species of deep demersal fish (Figure 2). Fishing scenarios of F25, F40, and F75 varied little in their spatial impacts or number of groups affected (Figure 2). No predators of deep demersals were affected by their removal.

The qualitative effects of increasing grenadier fishing mortality varied among model cells (Figure 3). Only one of the five model cells in which two or more groups were affected had deep demersal fish present. In this cell (14), decreasing abundance of deep demersals led to increased copepod abundance, a prey species of the target group. This increase was also associated with increased microzooplankton and phytoplankton abundance (Figure 3). The direction of change for microzooplankton varied across model cells, however. Plankton groups were affected at low levels but in both directions.

Fishing the deep demersal group decreased stability and increased return rate very slightly, but only in the most severe fishing scenario (Table 2). Reactivity was lower when the target group was fished at any level, however reactivity declined to a minimum when it was fished at MSY, and increased as depletion increased. Overall, these changes in stability were quite small.

NEARSHORE MISCELLANEOUS FISH

A fishery on the nearshore demersal fish group (croaker) attained MSY of 2000 mt with an annual fishing mortality of 0.1 (appendix 1). This level of fishing reduced the biomass of the functional group to 40 percent of the status quo equilibrium biomass of 20000 mt. Fishing the target group led to increased abundance of the shrimp group, which is a prey group for nearshore demersals. The shrimp group includes all crangon, mysid, and pandalid shrimp species. This increased biomass led to higher yields of the shrimp fishery by up to 12 percent (Figure 4).

Because shrimp biomass increased with fishing the nearshore demersal group, at least one functional group was impacted in 27 model cells (the majority of the group's distribution in CCAM, Figure 5). Besides shrimp, most impacts were on invertebrate plankton groups. Benthic detritivores, benthic bacteria, and octopi were all impacted in at least one scenario. Of these, only benthic detritivores were a prey group for croaker in the model. Impacts were more concentrated in central California region, particularly in cells whose boundaries represent those of the Gulf of the Farallones and Northern Monterey Bay National Marine Sanctuaries. An intermediate fishing scenario (F40) resulted in the greatest perturbation to other functional groups (Figure 5E).

The areas of greatest perturbation occurred where densities of both shrimp and nearshore demersal fish were relatively high (Figure 6, cells 24, 39, and 46). In many cases, perturbed groups tracked the target group's productivity with greatest changes occurring when croaker were fished to B40. Overall, microzooplankton had the largest proportional changes in biomass. These perturbations occurred in cells

with very low densities of microzooplankton, however. Therefore, the change in absolute biomass was quite small.

Fishing the miscellaneous nearshore demersal fish group did not affect ecosystem return rate, but did decrease stability (increase in the second stability metric, Table 2). Reactivity declined at low fishing levels, and increased with higher fishing pressure. All levels of fishing had lower reactivity than the status quo scenario, however.

SHORTBELLY ROCKFISH

Shortbelly MSY was about 675 mt, and occurred under a fishing mortality of 0.2 per year. This coincided with a reduction in shortbelly biomass to 20 percent of the status quo. Increasing fishing mortality to 1 was required to completely deplete shortbelly (Appendix 1). A shortbelly fishery did not affect yields of any other fisheries.

Ecosystem-wide abundance of functional groups was not influenced by any shortbelly fishing scenarios. Up to four functional groups were affected in individual cells, mostly in central California where shortbelly are distributed in CCAM (Figure 1, 7). More cells and functional groups were affected as fishing mortality increased (Figure 7). As in the previous two fisheries, the greatest number of groups was affected in the Gulf of the Farallones and Northern Monterey Bay National Marine Sanctuary cells (24 and 39). Only two of the five cells in which two or more functional groups were affected overlapped with status quo shortbelly distribution in the model (Figure 8). Similar to the croaker fishery, we saw the largest proportional changes in the microzooplankton group, which was not a prey group for shortbelly. These changes occurred in cells with relatively low densities of microzooplankton, however. The greatest direct effect of removing shortbelly was increased copepod abundance. Other prey groups of shortbelly that were affected included benthic detritivores, benthic bacteria, and pelagic bacteria.

Of the three target species, fishing on shortbelly had the greatest impacts on ecosystem stability. Despite its limited distribution in the model, completely depleting shortbelly led to an increased ecosystem return rate (Table 2). Increasing fishing pressure also incrementally increased the other stability metric. Reactivity tracked with fishing pressure as in the previous two target groups. Low levels of depletion led to low reactivity, but increased fishing increased reactivity.

DISCUSSION

We explored the effects of new fishery development on three new target groups in the California Current. Overall, we found fairly low magnitude impacts on a limited number of functional groups in the model. Even the most severe fishing scenarios affected fewer than 10 percent of functional groups. We saw the most widely distributed effects on copepod abundances, across the fisheries and model domain. The effects did not propagate to higher trophic levels, however. Only one of three fisheries led to changes in fishery yields of any other functional group in the model. Despite these limited impacts, these fishing activities generally decreased ecosystem stability.

Studies focusing on large biomass low trophic level species and associated fisheries have described larger ecosystem-wide impacts of fishing on those groups [13]. Using the same model of the California Current to explore more abundant forage groups, Kaplan et al. (this volume) saw changes of greater than 20 percent in many groups, in particular predators of forage species. Our results did not show such widespread or dramatic changes. We propose two not mutually exclusive explanations for the limited effects of fisheries

for the three groups we explored here. First, and most simply, biomass for these groups is low relative to other forage groups in the model, and low relative to groups explored in previous studies. For the three cases we described, our modeling results suggest these groups may be functionally redundant with other prey species [17]. This necessarily means that fishery removals will be a smaller perturbation to ecosystem total biomass, and thus minimize impacts on other functional groups. Second, our current model's structure may be insufficient to capture local variation in space and time that could impact food web structure heterogeneously along the west coast.

The low biomass of the three functional groups we explored here identifies some constraints in the model structure that limited our ability to capture potential effects of new fisheries on these target groups. The fishery targeting nearshore demersal fish resulted in increased catches of shrimp, with no variation across individual model cells. This finding could be somewhat misleading due to Atlantis constraints on species distributions and movement. Spatial distributions of functional groups are determined seasonally in the model. These parameters allocate total biomass by functional group to individual cells proportionally. Therefore, a group could be strongly affected by fishing on the new target species within a season, but at the beginning of the next quarter, biomass is reallocated across all the cells in the model according to seasonal distribution. This limits the ability of fishing on groups with limited spatial distributions to affect densities of prey or predator species that have seasonal components under our current parameterization. These seasonal parameters apply to all vertebrate groups, euphausiids, cephalopods, and shrimp. If we could turn off seasonal movements in the model, we could test how much seasonal reallocation of biomass contributed to the changes we did (or did not) observe. Alternatively, density dependent and prey dependent movements are features of the model we have not fully explored, and these could also capture meaningful responses of locally depleted functional groups.

Similarly, seasonal constraints and the limited ability to capture spatially heterogeneous changes in functional groups may also contribute to our inability to observe changes in predator biomass of target species. Fishing shortbelly could potentially have locally negative impacts on seabirds that rely on shortbelly as a prey source during key breeding seasons, for example [14,18]. These effects could be masked in the model by re-allocation of seabird biomass across the model cells in accordance with their seasonal distribution in each quarter, or by the large size of the model cells compared to breeding grounds.

Similarly, our application of fishing mortality in this version of the model also likely constrained functional group and fishery responses. We implemented somewhat rudimentary fleet dynamics in CCAM in this study. We specified the functional groups targeted by each fleet, and area closures were implemented by fleet based on gear-type. Fishing mortality was represented by a constant (daily) rate by functional group and fleet. This resulted in a constant proportion of biomass removed across all cells that were not closed to the fishery. Therefore, catches tracked biomass linearly and proportional changes in catches had to be constant across the model domain. Small biomass groups and those with limited spatial distributions in a larger model may be particularly sensitive to these types of generalizations.

We saw disproportionately large biomass effects in central California, either in spite of or because of these model constraints. Our model predictions could have implications for the food web in this region, particularly in the Gulf of the Farallones and the northern region of the Monterey Bay National Marine Sanctuaries. These sanctuaries provide habitat for many species of conservation concern, such as seabirds and marine mammals [42,43]. However, the cause of these findings warrants further investigation before any strong conclusions can be drawn. Even if the magnitudes of the impacts of new fishing activities are underestimated or captured imperfectly by CCAM, our work identifies regions of the coast that are more likely to be impacted. This kind of knowledge may aid regional managers in making proactive decisions, for example monitoring particular functional groups for evidence of impacts of fishing.

Impacts on invertebrate functional groups should be interpreted as qualitative expectations, rather than exact predictions, however. Nearly all functional groups that responded to reductions in target species biomass were highly productive and highly variable within a year or across years. These traits lead to quick responses to changes in the ecosystem, but also lead to dynamics that are difficult to predict, as indicated by a single functional group responding in different directions across multiple model cells.

Our work represents a first step toward understanding how fishing target species on high and low biomass groups could impact ecosystem stability and biomass distribution in a spatially explicit ecosystem model. A next step would be a comparative analysis using the findings in Kaplan et al. (this volume) to motivate a spatially explicit analysis of fishing large biomass forage groups such as sardine, myctophids, and krill. We could also compare the effects of fishing on ecosystem stability across a range of biomass removals, and explore stability in a more spatially explicit way within and across fishing scenarios.

Adopting ecosystem based management approaches and implementing fishery ecosystem plans will necessarily result in identifying trade-offs between consumptive and non-consumptive uses in large marine ecosystems. Here we demonstrated the effects of three potential fisheries that our ecosystem models suggest will have relatively low impacts on the food web at the ecosystem scale. Instead, trade-offs may occur across space, with potentially cascading effects on planktonic and benthic invertebrate groups. Our results do not provide definitive predictions on the impacts of new fisheries, but identify regions and groups that could be targeted for monitoring potential impacts if these fisheries were to develop. More importantly, this work provides a necessary framework for evaluating the effects of fishing on ecosystem stability and the distribution of biomass across a spatially heterogeneous large marine food web.

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Table 1. Summary of fishing scenarios and target groups. Biomass and yield indicated are for status quo (SQ) model run. M indicates annual natural mortality rate. Maximum sustained yield (MSY) was determined using all fishing scenarios for each target group, and FMSY indicates the fishing mortality rate at MSY. Annual fishing mortality required to obtain 75, 40, 25, and 0 percent depletion is indicated by F75, F40, F25, and F0, respectively.

Target Group	SQ Biomass (mt)	SQ Yield (mt)	M	MSY (mt)	FMSY	F75	F40	F25	F0
Deep demersal fish	183562	2117	0.1	2055	0.03	0.01	0.03	0.04	0.1
Misc. nearshore fish	20920	206	0.62	905	0.12	0.04	0.1	0.12	0.24
Shortbelly rockfish (<i>Sebastes jordani</i>)	16434	0.1	0.35	687	0.2	0.05	0.1	0.2	1

Table 2. Ecosystem stability metrics by target species and fishing scenario. Stability metrics were based on the community (interaction) matrix estimated from time-series models. Return rate and Stability both describe the asymptotic behavior after a perturbation and Reactivity describes short-term transient dynamics. In all cases, smaller values indicate greater stability.

Target Species	Metric	SQ	F75	F40	F25	F0
Deep demersal fish	Return Rate	0.754	0.754	0.754	0.754	0.755
	Reactivity	0.594	0.587	0.581	0.583	0.587
	Stability	0.045	0.046	0.046	0.046	0.047
Nearshore misc. fish	Return Rate	0.754	0.754	0.753	0.754	0.753
	Reactivity	0.594	0.576	0.581	0.579	0.586
	Stability	0.045	0.047	0.046	0.047	0.045
Shortbelly rockfish	Return Rate	0.754	0.753	0.753	0.754	0.760
	Reactivity	0.594	0.583	0.575	0.582	0.591
	Stability	0.045	0.045	0.046	0.046	0.049

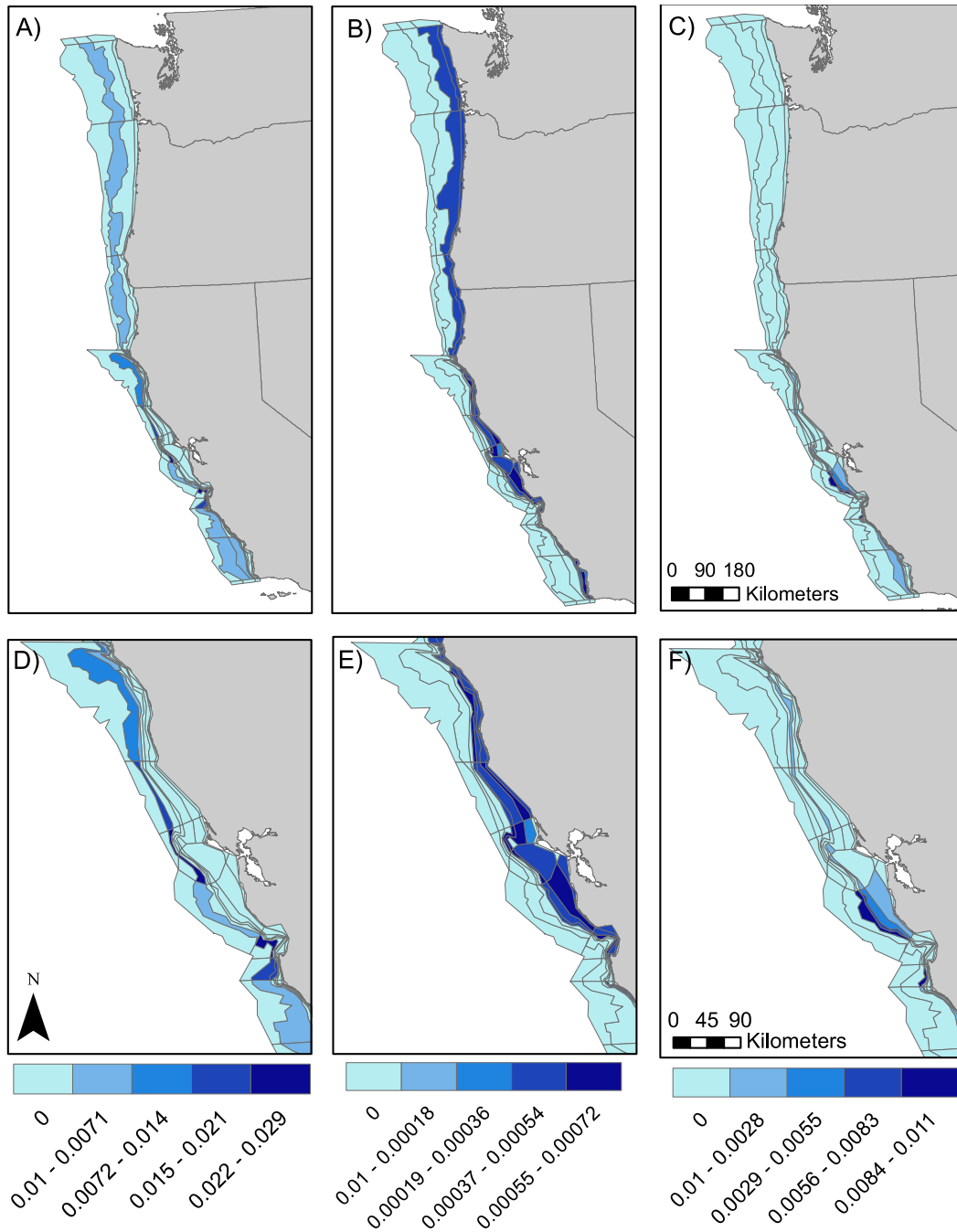


Figure 1. Status quo distribution of new potential target groups (deep demersal fish, nearshore miscellaneous fish, and shortbelly rockfish). Top panels illustrate distribution in the full model domain (A, B, C). Bottom panels show distribution within Central California region (D, E, F). Deep demersal fish densities were highest in slope cells (A, D), nearshore miscellaneous fish were limited to coastal areas (B, E), and shortbelly rockfish were concentrated in Central California (C, F). Legend below each panel indicates densities in kg/m².

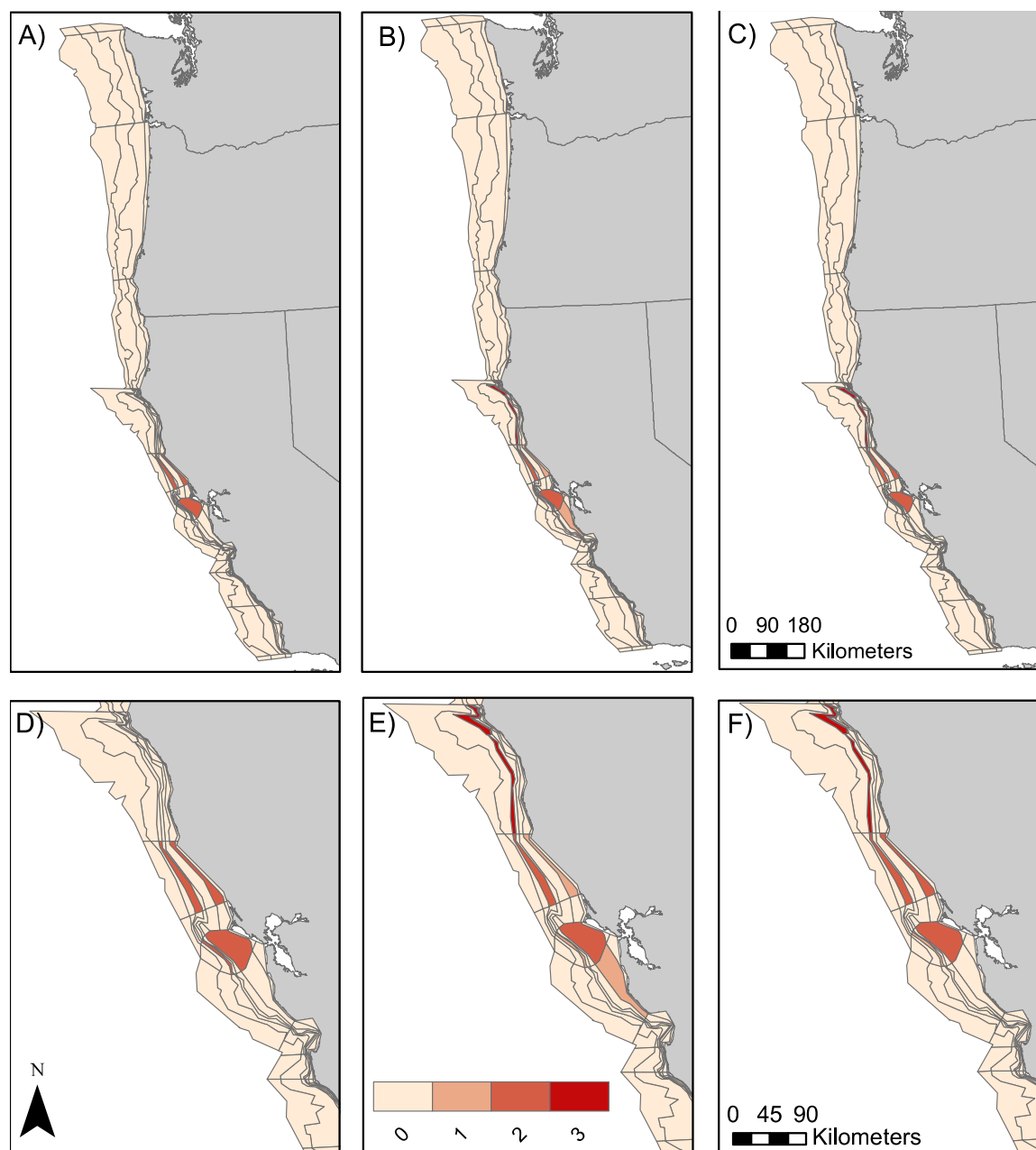


Figure 2. Number of functional groups affected by a fishing deep demersal fish at three fishing levels (threshold of 10 percent change) by cell. Fishing scenarios represented are F75 (A, D), F40 (B, E), and F25 (C, F). Density of color indicates increasing number of functional groups affected, as indicated by legend. Top and bottom panel extents as in Figure 1.

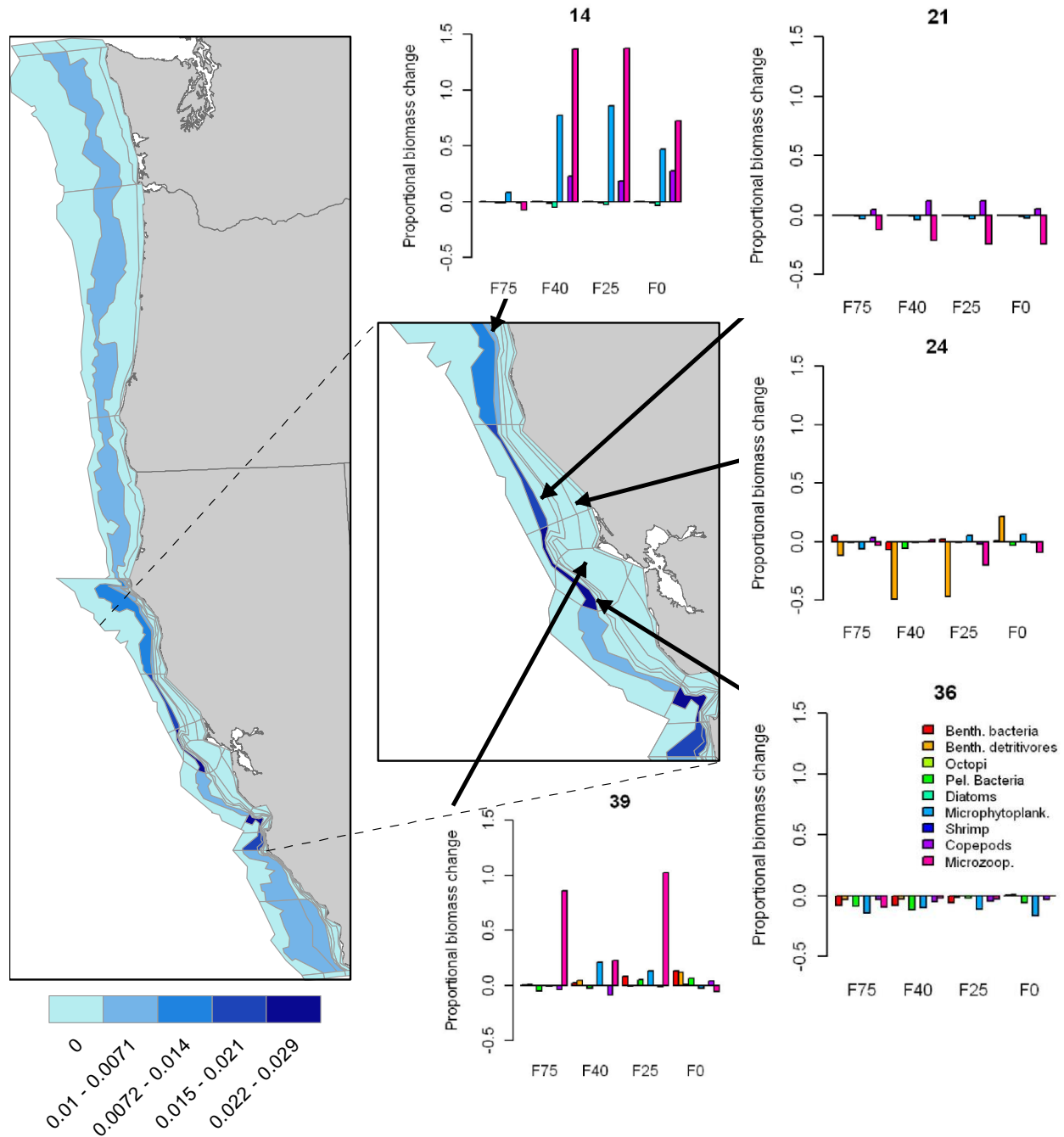


Figure 3. Effects of fishery targeting deep demersal fish on proportional biomass of other functional groups by cell. Map shading indicates deep demersal fish density, as in Figure 1. Nine functional groups were affected by at least one fishing scenario in at least one box across all three target species. For consistency, all nine groups are shown in all panels regardless of level of impact.

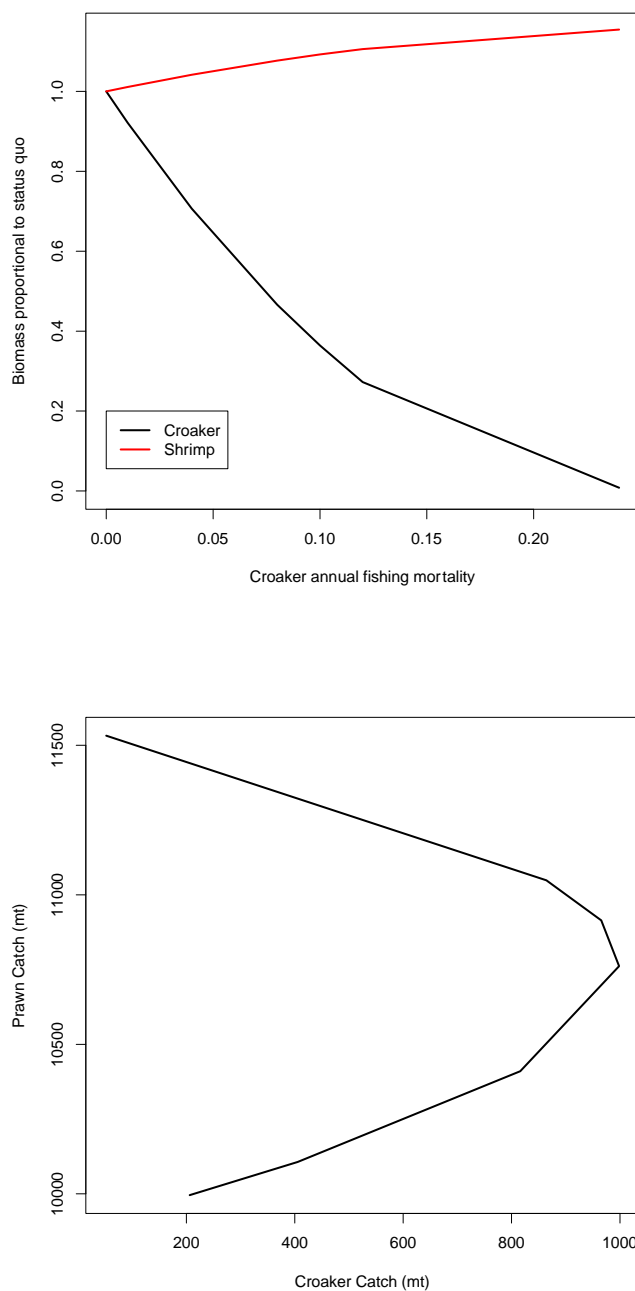


Figure 4. Changes in biomass and yield as a function of increased fishing mortality on nearshore miscellaneous fish (mostly white croaker). Shrimp biomass increased about 15 percent as white croaker biomass declined with fishing (A). Shrimp catches increased as croaker catches increased to MSY (B). Shrimp catches continued to increase as croaker catch declined and the population became depleted.

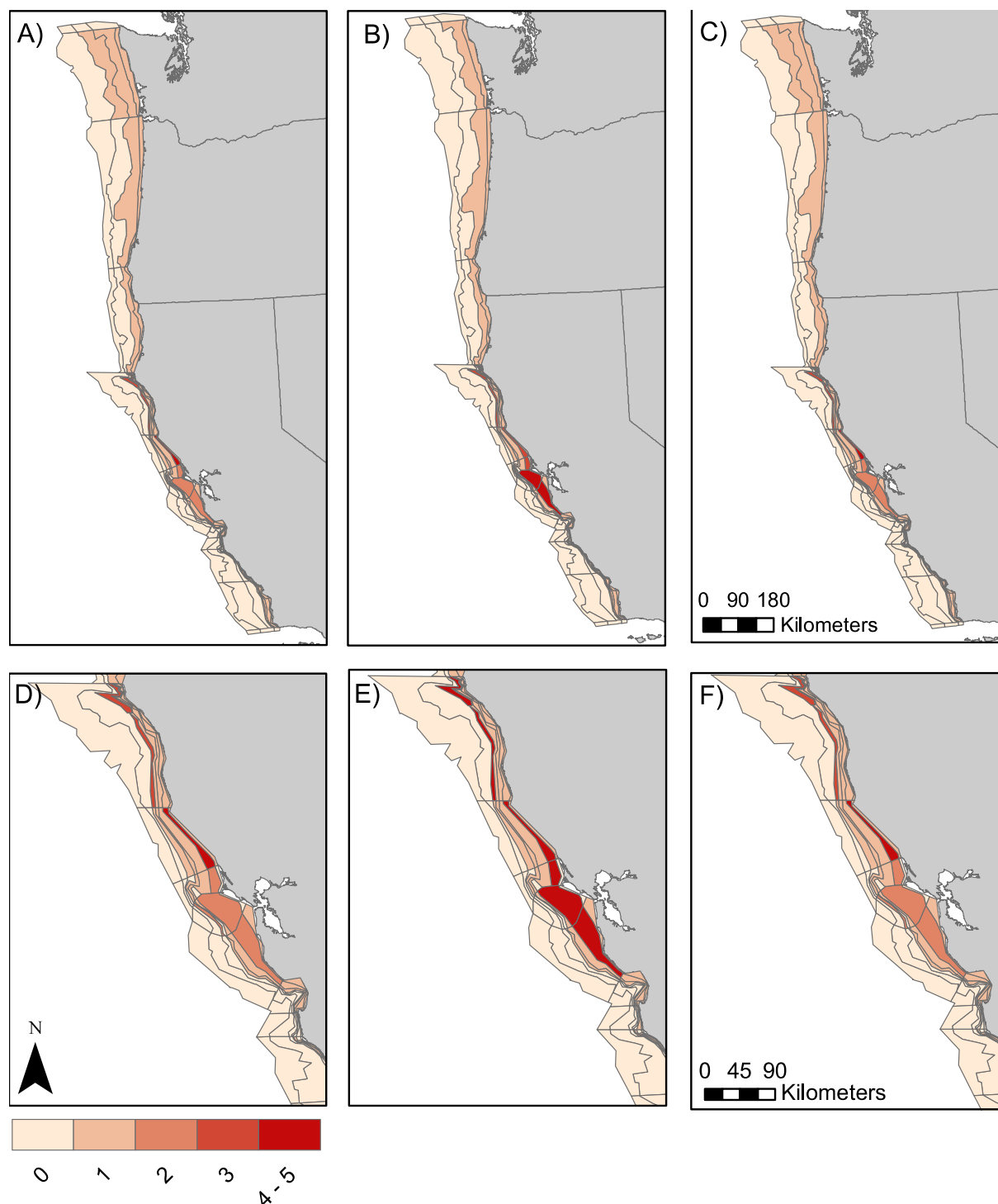


Figure 5. Number of functional groups affected (threshold ± 10 percent) by introducing a fishery targeting the nearshore miscellaneous fish group, by cell. Fishing scenarios represented are F75 (A, D), F40 (B, E), and F25 (C, F). Density of color indicates increasing number of functional groups affected, as indicated by legend. Top and bottom panel extents as in Figure 1.

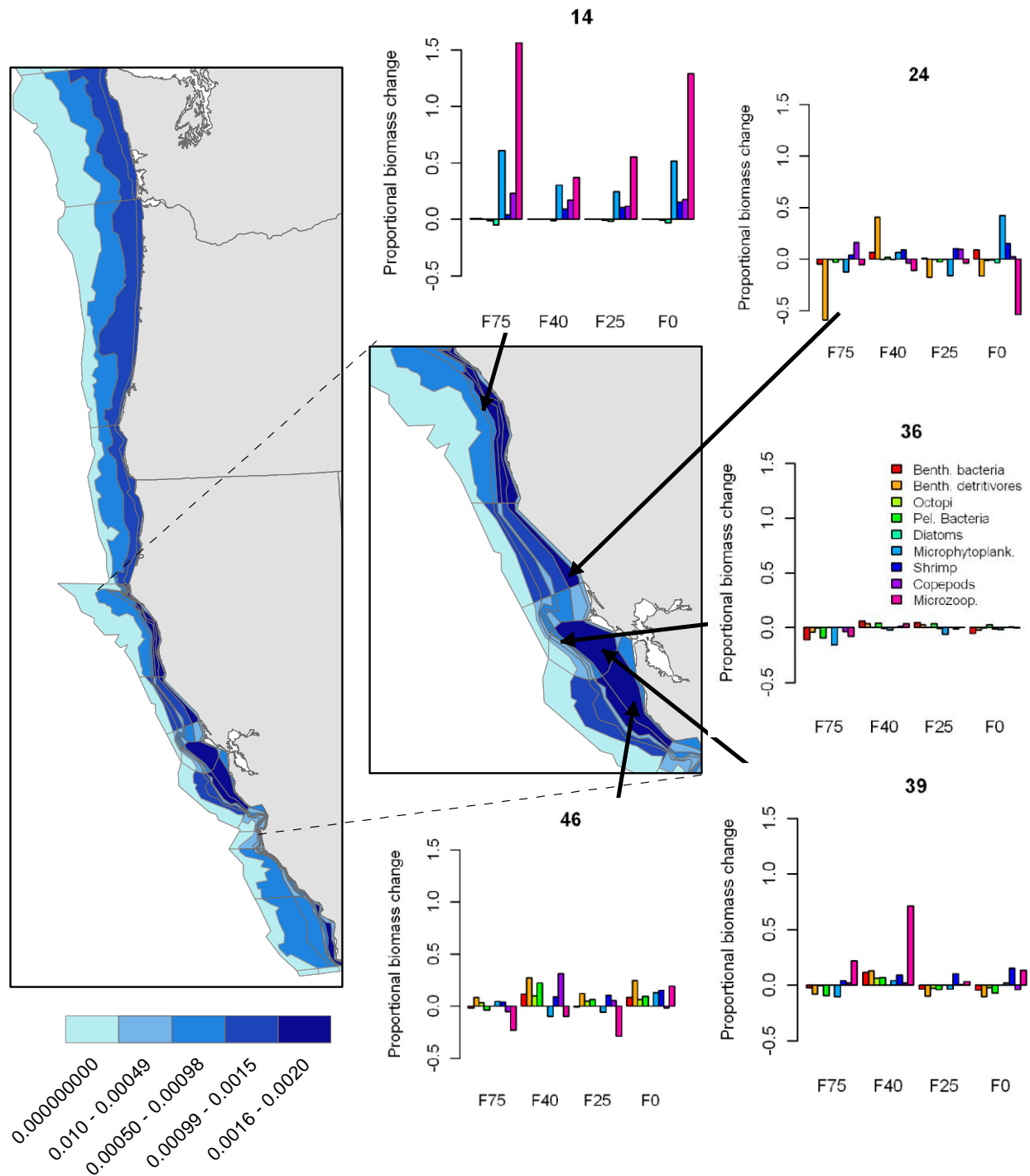


Figure 6. Effects of fishery on nearshore miscellaneous demersal fish group on functional groups by cell for cells with more than two functional groups affected. Maps show summed densities for the target fish group and prawn in status quo scenario. Surrounding plots indicate cascading effects were more common in cells with high densities of both shrimp and the targeted group. Bar coloring is consistent with Figure 4.

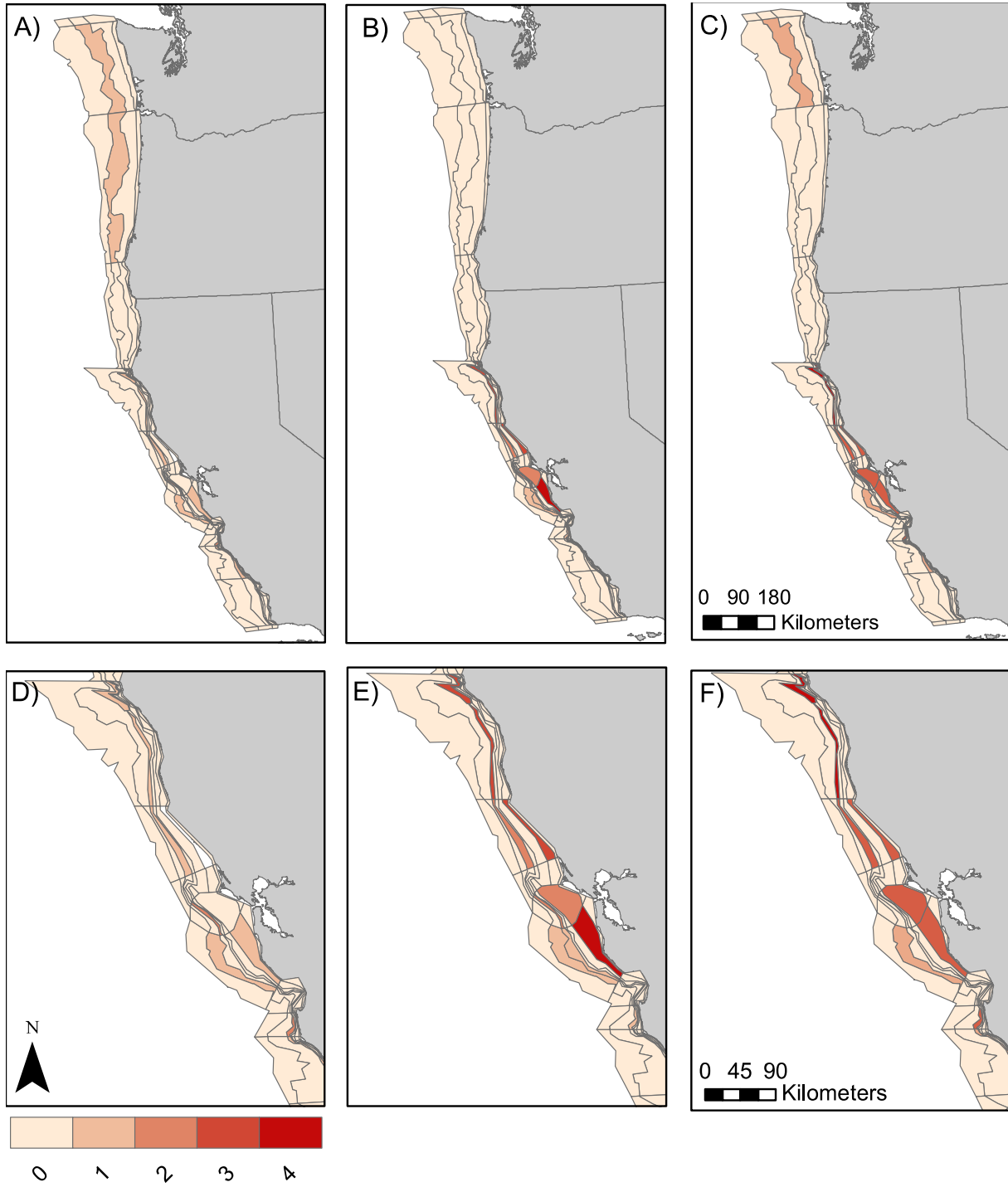


Figure 7. Number of functional groups affected (threshold ± 10 percent) by introducing a shortbelly rockfish pacific fishery, by cell. Fishing scenarios represented are F75 (A, D), F40 (B, E), and F25 (C, F). Density of color indicates increasing number of functional groups affected, as indicated by legend. Top and bottom panel extents as in Figure 1.

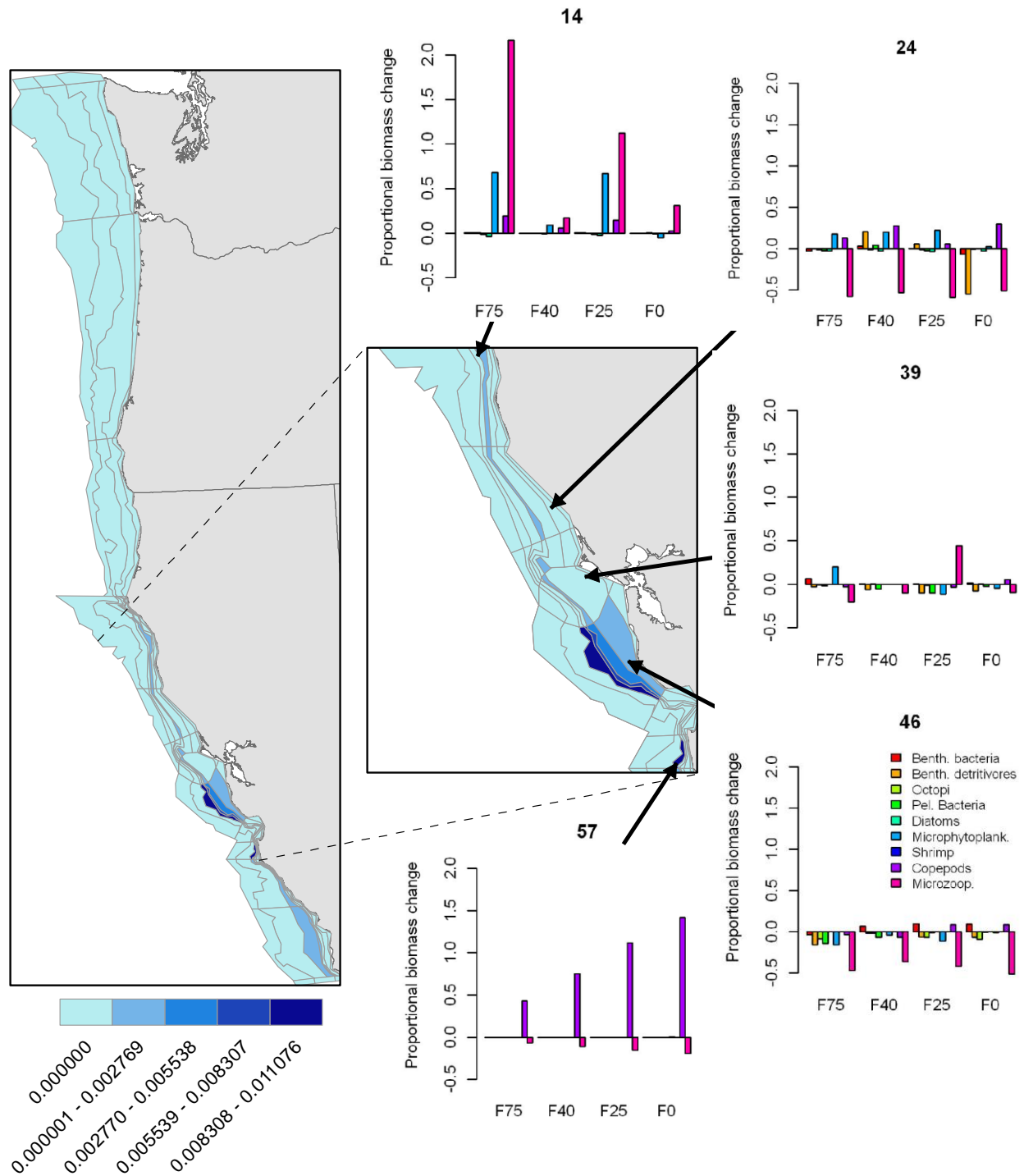


Figure 8. Effects of shortbelly rockfish fishery on proportional biomass of functional groups for cells with two or more impacted function groups. Maps indicate shortbelly density in status quo scenario as in Figure 1. Bar coloring consistent with Figure 4.

APPENDIX A: FINDING MSY/FISHING SCENARIOS

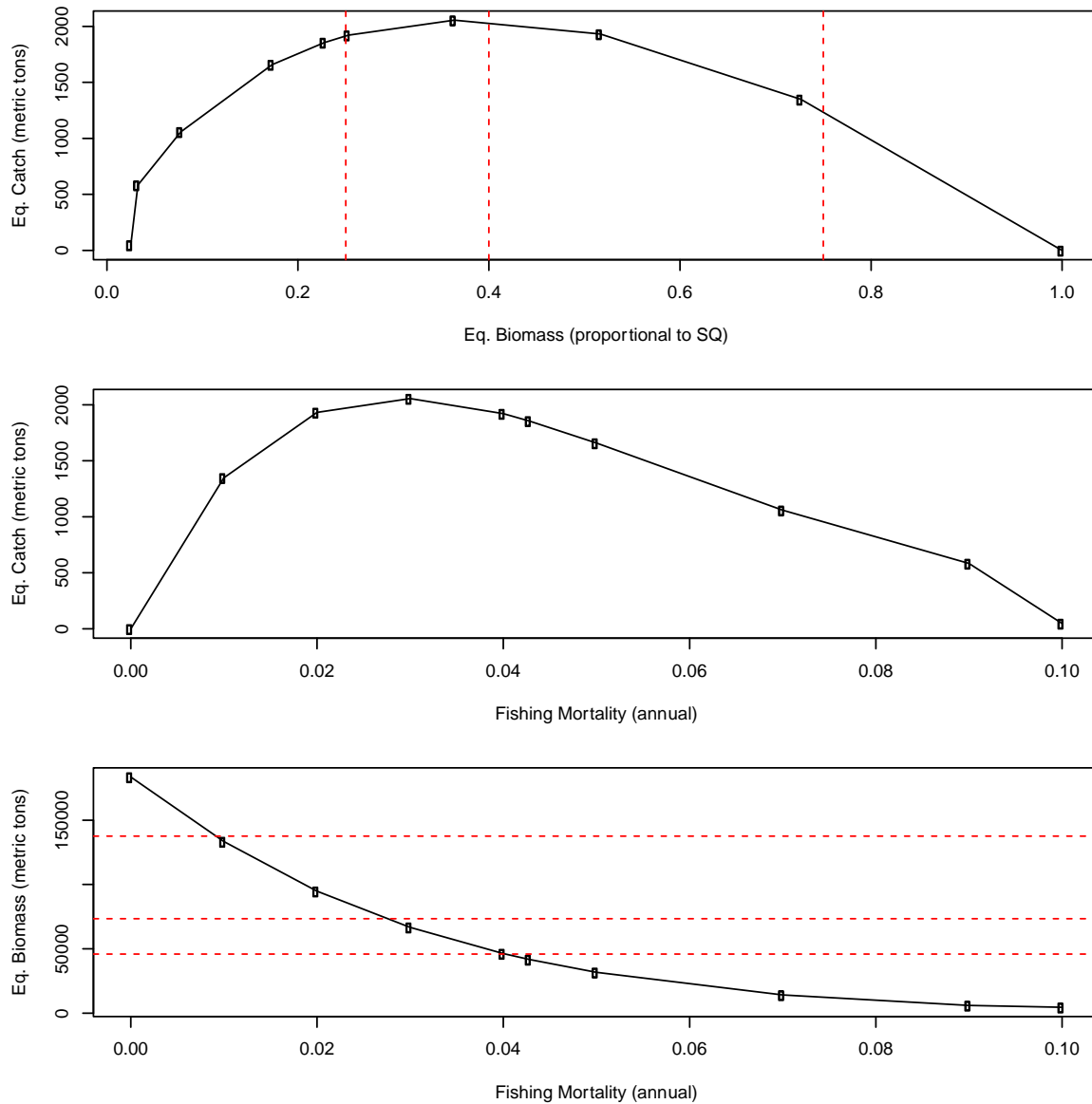


Figure A1. Fishing scenarios for deep demersal fish. Top panel shows equilibrium catch as a function of biomass proportional to the status quo scenario equilibrium. Vertical red lines indicate catch at 25, 40, and 75 percent of status quo. Middle panel shows the relationship between catch and fishing mortality. Maximum sustained yield is the peak of the curve. Bottom panel shows biomass as a function of increasing fishing mortality. Horizontal red lines indicate scenarios as in top panel, indicating fishing mortality required to meet the target biomass.

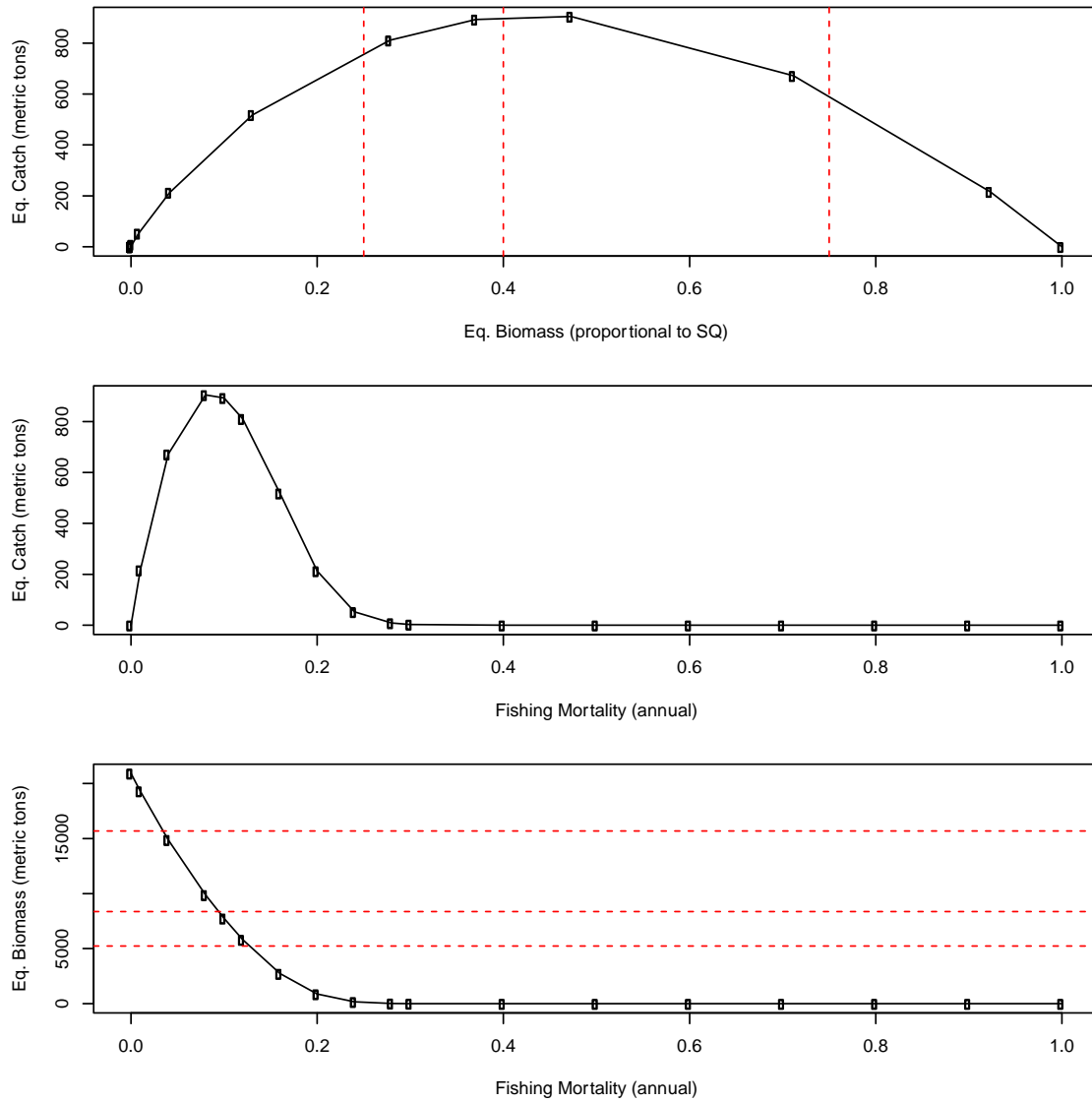


Figure A2. Fishing scenarios for nearshore miscellaneous demersal fish. Panels and axes as in Figure A1.

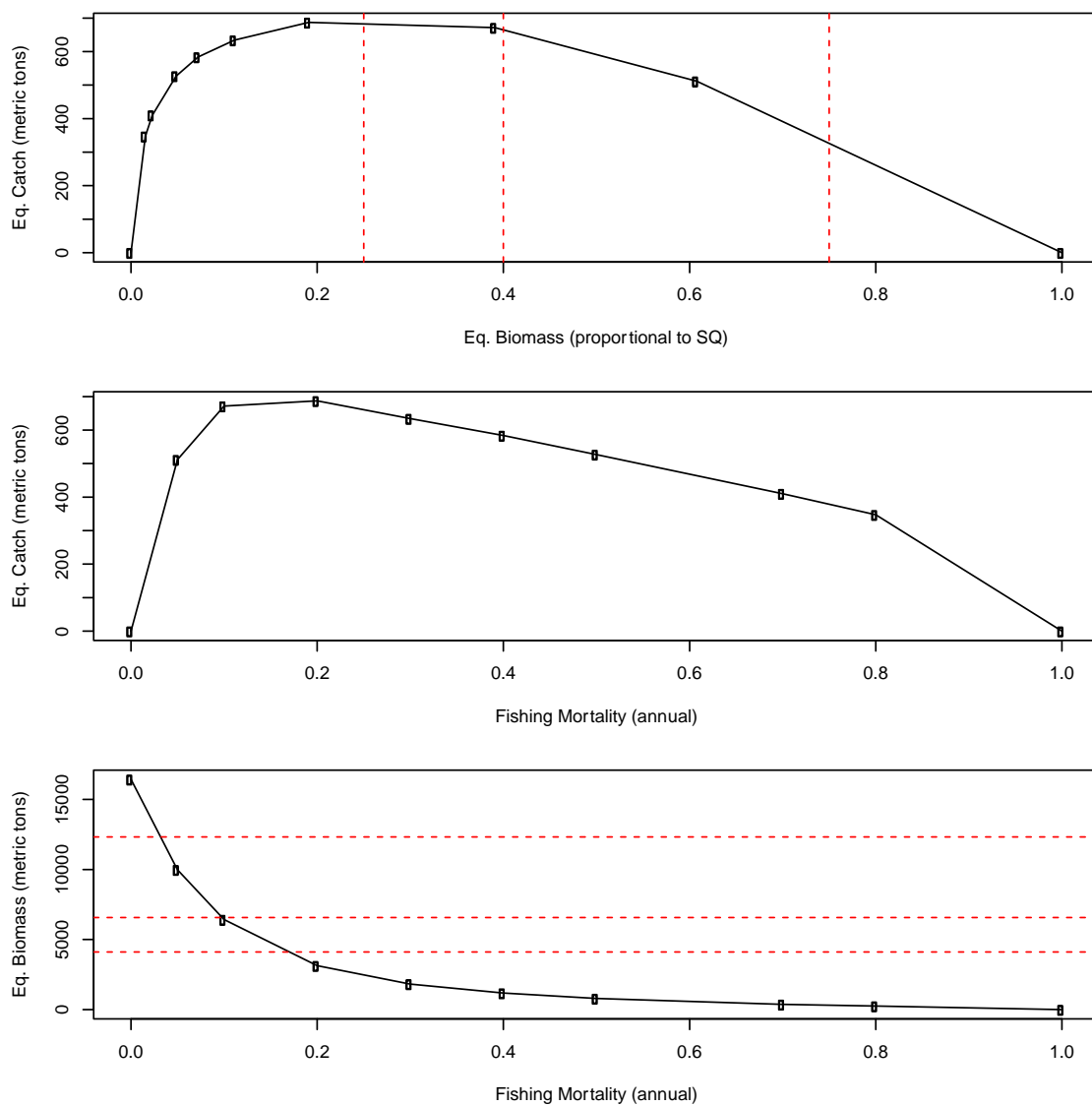


Figure A3. Fishing scenarios for shortbelly rockfish. Panels and axes as in Figure A1.